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Land Information System (LIS) Development Plan

FY13–FY17

John B. Eylander

October 2013

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Land Information System (LIS) Development Plan

FY13–FY18

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Final Report

Prepared for US Air Force Weather Agency
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Abstract

In 2007, the Air Force Weather Agency (AFWA) approved a plan, collaborative with NASA Goddard Space Flight Center (GSFC), to partner on development of the Land Information System (LIS), an advanced software framework capable of supporting an operational and research-mode Land Data Assimilation System (LDAS) for weather and climate studies. The partnership led to the development of a structured 5-year plan to continue developing the LIS with newer science and software capabilities to improve the land surface characterization products at AFWA. The results were highly successful, leading LIS to be characterized as one of the most advanced LDAS systems available. This document builds on the successes of the initial 2007 LIS Development Plan (LDP07) and outlines incremental steps toward achieving a new set of goals not only to enable science and engineering achievements but also to deliver new capabilities of supporting soldiers and decision makers at all echelons of military support, from command level to small units. The new support opportunities include support for geospatial intelligence needs, including global drought (agricultural and hydrological) and hydrometeorology analysis and prediction, interfaces that enable LIS to support Army applications of maneuver support, additional work on the coupled LIS-WRF interfaces to improve support to dust lofting and brownout, as well as other infrastructure upgrades.

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Preface

This paper was written for the US Air Force Weather Agency as a deliverable for MIPR #F3HRA1174G001 and is a follow on to the original LIS Development Plan approved by the US Air Force Weather Agency Director of Plans and Programs (A8) 25-Oct-2007.

The document was developed by John Eylander (Terrestrial and Cryospheric Sciences Branch, Janet Hardy, Chief), with the support of technical editor Emily Moynihan (ERDC contractor), US Army Engineer Research and Development Center, Cold Regions Research and Engineering Laboratory (ERDC-CRREL). At the time of publication, Dr. Justin Berman was Chief of the Research and Engineering Division. The Deputy Director of ERDC-CRREL was Dr. Lance Hansen, and the Director was Dr. Robert Davis.

COL Jeffrey R. Eckstein was the Commander of ERDC, and Dr. Jeffery P. Holland was the Director.

The author would like to acknowledge the individuals who reviewed and provided significant input on this report, including Dr. Jeffrey Cetola, AFWA 16th Weather Squadron; Dr. Christa Peters-Lidard, NASA Goddard; Dr. Sujay Kumar, SAIC and NASA Goddard; and Michael Shaw, SAIC (NASA/AFWA).

Nomenclature

AF	Air Force
AFWA	Air Force Weather Agency
AGRMET	AFWA Agricultural Meteorology Model
AMPS	AFWA Merged Precipitation System
AMSR-E	NASA Advanced Microwave Sounder/Radiometer for Earth Observing System (EOS)
ANSA	AFWA-NASA Snow Algorithm
ARTEMIS	Army Terrestrial-Environmental Modeling and Intelligence System
CDFS-II	Cloud Depiction and Forecast System Version II
CHL	Coastal Hydraulic Laboratory
CLM	NCAR Community Land Model
CMORPH	CPC Morphed precipitation analysis model
CPC	NOAA Climate Prediction Center
CRREL	Cold Regions Research and Engineering Laboratory
CRTM	Community Radiative Transfer Model
DMSP	Defense Meteorological Satellite Program
DoD	Department of Defense
EDCSS	Environmental Data Cube Scenario Simulator
EnKF	Ensemble Kalman Filter
EOS	Earth Observing System
ERDC	Engineer Research and Development Center
ESMF	Earth System Modeling Framework
ET	Evapotranspiration
GEOPRECIP	Geostationary Satellite-based Precipitation analysis model
GMAO	NASA Goddard Modeling and Assimilation Office

GSL	Geotechnical and Structures Laboratory
GSSHA	Gridded Surface and Subsurface Hydrologic Analysis
IC	Intelligence Community
IMERG	Integrated Multi-Satellite Retrievals for GPM
ISR	Intelligence, Surveillance, and Reconnaissance community
JCSDA	Joint Center for Satellite Data Assimilation
LDAS	Land Data Assimilation System
LIS	Land Information System
LSM	Land Surface Model
LVT	Land surface Verification Toolkit
MDMP	Military Decision-Making Process
MODIS	NASA Moderate Resolution Imaging Spectroradiometer
NASA	National Aeronautics and Space Administration
NCAR	National Center for Atmospheric Research
NCEP	National Centers for Environmental Prediction
NOAA	National Oceanic and Atmospheric Administration
NPOES	National Polar-orbiting Operational Environmental Satellite System
NWP	Numerical Weather Prediction
R&D	Research and development
SBIR	Small Business for Innovative Research
SFCTMP	AFWA Surface Temperature
SNODEP	AFWA Snow Depth model
SMOS	Soil Moisture and Ocean Salinity
SSMI/S	Special Sensor Microwave Imager/Sounder
WRF	Weather Research and Forecasting

1 Introduction

Developing community modeling systems for both the atmosphere and earth and implementing the community models at the Air Force Weather Agency (AFWA) are opening significant research-to-operations pipelines that are leading to major advances in numerical weather prediction; and unhindered, will lead to significant advances over the next decade. The now successful, mutually beneficial, mature partnership between AFWA and the National Centers for Atmospheric Research (NCAR) has already proven highly successful. The partnership increased the software transition effectiveness and significantly reduced the research-to-operations gap for transitioning new Weather Research and Forecasting (WRF) model capabilities into operations at AFWA. AFWA receives technology and expertise from a world-class team of industry-leading numerical weather prediction and data assimilation scientists while supporting cutting edge research and development that is second to none and often results in rapid transition to operational capability.

The partnership between AFWA and the National Aeronautics and Space Administration (NASA) is similar. AFWA and NASA have met mutually beneficial goals of developing a common software infrastructure to facilitate the rapid development, integration, and transition of new terrestrial modeling capabilities from research to operations. The partnership has positioned AFWA with many advanced terrestrial characterization capabilities that offer new opportunities to support key DoD missions and mission partners. An important and successful result of the AFWA and NASA partnership has been the integration of the AFWA Land Information System (AFWA-LIS) into operations, establishing a common software framework for hydrometeorological characterization between the research and operations communities. The LIS software has become a community standard, similar to the WRF model framework, enabling AFWA to benefit from industry-leading terrestrial modeling R&D available through the NASA community. Hydrometeorological research is already demonstrating promise—greatly improving weather forecasting capabilities that will dramatically improve AFWA’s ability to support ground-based DoD and Intelligence Community assets worldwide.

The AFWA-LIS is an expanded DoD version of the NASA LIS software—a sophisticated Land Data Assimilation System (LDAS) framework—capable of generating analyses of “weather” profiles for surface and near subsurface soils. These profiles include the computation of the surface energy balance (latent, sensible, and ground heat flux), soil moisture and temperature, and (in the future) vegetation characteristics. The AFWA-LIS development was guided by requirements and resources supplied by NASA, AFWA, and the Army to create a system capable of supporting climate research, weather analysis and prediction, and Army terrestrial environment products that will initialize decision support applications. AFWA produced a 5-year plan in 2007, providing guidance for future infrastructure investment for LIS, ending in FY2012. NASA’s success in achieving the goals outlined in the FY07–12 plan necessitates a new, medium-term outlook to direct technology progress for the next 5 years. This plan will ensure continued LIS improvements supportive of current and evolving Air Force, Army, and Intelligence Community terrestrial product requirements.

This updated plan builds off the success of the *FY07–12 LIS Development Plan*. It will encourage infrastructure capability enhancements while also outlining targeted developments to enable new support opportunities for Army, Air Force, and the Intelligence Community. New products are needed to support targeting, deployable force protection, maneuver and austere entry planning, water security, stability operations, and much more. This new focus on developing products should give terrestrial modeling output within the DoD a higher profile and enable new support for products not currently available in an operational environment.

Additionally, this plan is not specifically tailored toward AFWA. Rather, it will highlight the roles of several organizations as collaborators. The broader defense modeling and simulation and military planning communities need to fully embrace earth systems modeling enterprise products and capabilities for supporting soldiers and decision makers. Additional collaborators include laboratories within the US Army Engineer Research and Development Center and Army Research Laboratory.

2 Review

The initial LIS development plan focused on infrastructure, aiming to merge many AFWA analysis packages—the AFWA Snow Depth analysis (SNODEP) model, AFWA Surface Temperature analysis model, and Geostationary Satellite-based Precipitation (GEOPRECIP) analysis—into a single software package capable of handling all surface characterization. The outcome of the initial development plan provided lessons learned while delivering on most of its goals.

Improving the LIS global precipitation analysis was a key goal in the original plan. Accurately identifying and characterizing precipitation is a critical component to many hydrometeorological models or analyses. In LIS, the accuracy of the precipitation inputs is highly important because the hydrologic model physics are highly sensitive to small changes in water budget. AFWA improved precipitation analysis capabilities in LIS by using the NOAA Climate Prediction Center (CPC) Morphed precipitation analysis (CMORPH) model as an enhancement to the Defense Meteorological Satellite Program (DMSP) Special Sensor Microwave Imager/Sounder (SSMI/S)-only precipitation analysis. The addition of CMORPH technology into the LIS modeling system increased the number of satellites used and decreased precipitation error in austere regions where surface observations were scarce. The new LIS precipitation methodology blends the CMORPH together with the AFWA GEOPRECIP-method precipitation analyses, GFS-based precipitation (AMPS—AFWA Merged Precipitation System), and surface-based gauge observations to create a merged global LIS precipitation analysis. The partnership forged with NOAA CPC and the collaborative use of CMORPH will pave the way for integrating into AFWA operations future advances in remotely sensed precipitation.

Another focus in the original plan was to add and to exploit new assimilation methods for incorporating remotely sensed land surface measurements, including soil moisture, surface temperature, and other parameters. NASA successfully integrated the NASA Goddard Modeling and Assimilation Office (GMAO) Ensemble Kalman Filter (EnKF) (Kumar et al. 2008) with LIS. This delivered a first-ever operational capability to assimilate remotely sensed soil moisture observations from passive microwave sensors (e.g., NASA Advanced Microwave Sounder/Radiometer for

Earth Observing System [EOS]—AMSR-E) that have adequate soil moisture detection frequencies (6, 10 GHz). The addition of the EnKF capability enabled NASA to successfully assimilate remotely sensed soil moisture observations from the NASA AMSR-E and Navy WindSat passive microwave sensors. Furthermore, it allowed surface skin temperature observations from the NASA Moderate Resolution Imaging Spectroradiometer (MODIS) sensor and geostationary-orbiting platforms. NASA also successfully assimilated hourly skin temperature observations from their research global cloud analysis system, similar to the AFWA Cloud Depiction and Forecast System, Version II (Reichle et al. 2010). The LIS-EnKF capability also enables assimilating observations beyond soil moisture and land surface temperature, including remotely sensed snow cover and snow depth observations, and could be used in the future to assimilate remotely sensed vegetation health information. A key advantage of an assimilation-based approach (as opposed to simple direct insertion of datasets) to land surface modeling is the ability to leverage the measurement uncertainties from remote sensors. Incorporating measurement uncertainties with model errors or parameter uncertainties will enable a broad ensemble modeling capability that will be able to support risk-based decision aids.

To allow higher resolution radiation budget computations, LIS needs to incorporate improved radiation diagnostic equations that better account for direct and diffuse incoming solar radiation and outgoing longwave radiation. LIS accomplished this by using higher resolution cloud optical properties information now available from the AFWA cloud analysis system. NASA added “two stream,” “four stream,” and correlated-k radiation algorithms into LIS that compute solar and terrestrial radiation while accounting more specifically for cloud optical properties. NASA also created a coupler for the Joint Center for Satellite Data Assimilation (JCSDA) Community Radiative Transfer Model (CRTM) software. This both will improve CRTM’s land surface characterization for space-based atmospheric and land observations and will enable it to assimilate land radiances in the future; it also will facilitate the calculation of higher resolution energy budgets closer to satellite pixel-level in LIS and will support improved surface energy budget computations versus the current, coarse resolution (based on 24 km AFWA World Wide Merged Cloud Analysis resolution) radiation computations.

Finally, the NASA LIS and NCAR WRF teams collaborated to create a coupling mechanism, using the NOAA Earth System Modeling Framework

(ESMF), where LIS and WRF can execute in a fully coupled, two-way interactive mode. This coupling enables more consistent data assimilation through prediction of the surface state variables concomitantly with the WRF forecast field. It also creates a significant opportunity by enabling both the multi-parameter and multi-model ensemble capabilities in LIS to support additional WRF-based ensemble members.

3 Purpose

This plan highlights some of the operational requirements and background for the AFWA terrestrial numerical modeling mission. It also provides an outline for future investment to advance Army, Intelligence Community, and Air Force planning capabilities. The goal of this plan is to lay the groundwork for continued migration towards a mature Air Force Weather Services capability to support the Army Operations Process and Intelligence Communities geospatial intelligence systems with products optimally tuned to provide decision support to all echelons. This includes continental scale to tailored small-unit products supporting mounted and dismounted operations. Existing weather-integrated decision support systems, especially those suited for supporting the Army, have not fully capitalized on available real-time surface characterization products; this is primarily because of issues of resolution and relevance. Unfortunately, the complexities of integrating available weather data and generating relevant decision-quality products has created a gap between supplier and user within operational DoD circles.

This planning document outlines a science-based approach to address these complexities and resulting gaps between supplier and user: it is aimed at increasing the production of decision-quality land surface weather products capable of direct integration into the military decision-making process (MDMP). Additional focus is provided toward characterizing analysis uncertainty, enabling commanders to understand environmental risks factors when creating command decisions. This document is supported by numerous Army and Air Force (AF) requirements and planning documents:

- Air Force Doctrine Document 2-9.1, 3 May 2006.
- Army Doctrine Publication ADP 5-0 (FM 5-0), May 2012.
- Army Doctrine Publication ADP 6-0, May 2012.
- Joint Army Regulation 15-10 and Air Force Instruction 15-157, *Climatological, Hydrological, and Topographic Services, Weather Support for the US Army*.
- Air Force Mission Directive 52, 16 March 2010.
- *AFW Characterize the Environment Enabling Concept*, Version 3.0, April 2006.

- *Air Force Enabling Concept for Weather Support to Army Modular Forces*, 16 September 2005.
- *Air Force Weather Requirements Oversight Council Priorities* (4, 5, 13, 14, 23, 25) 18 August 2004.
- *AFWA Strategic Plan* (Goals 5, 6), 12 April 2006.

The infrastructure supporting the AFWA modeling enterprise software is highly complex. It has a number of advanced capabilities that can be exploited with new product offerings. These new products can increase impacts-based weather knowledge services to the vast user base, directly or indirectly, through decision support systems (e.g., mobility applications). Further advances in technology in the Intelligence, Surveillance, and Reconnaissance (ISR) community will ultimately require higher resolution and increasingly accurate terrestrial-environmental analyses.

3.1 Current architecture description

Initial LIS capabilities (prior to AFWA investment) were significantly different from the current configuration options available in the LIS architecture in FY12 (Fig. 1). AFWA investment in LIS has also enabled a broad technology sharing opportunity among the NASA, AFWA, Army, NOAA, university, and corporate research sectors. The LIS software has become the “go to” framework for land data assimilation.

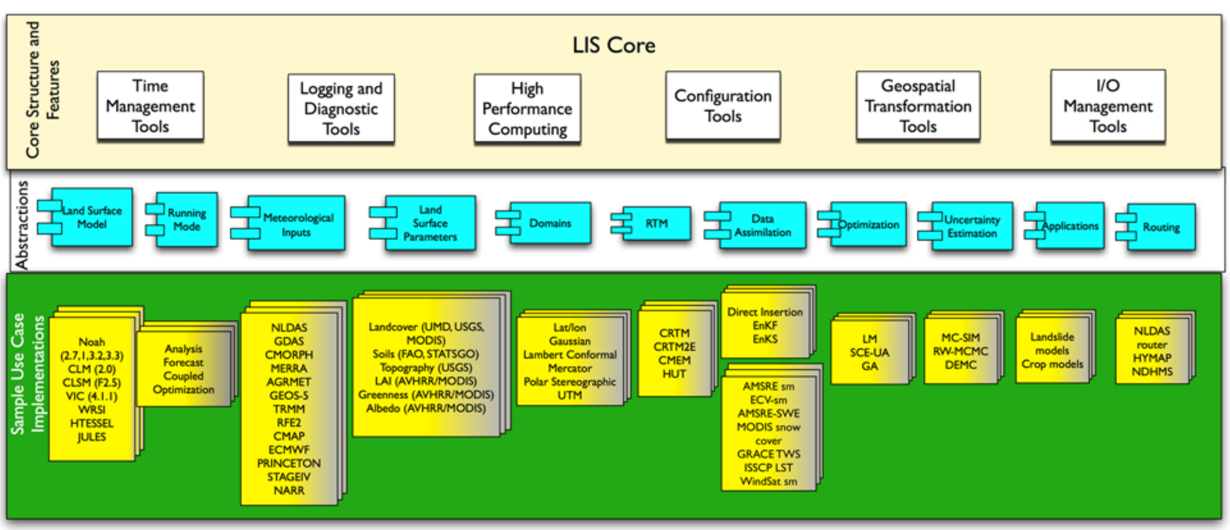

Figure 1. LIS framework.

The AFWA-LIS is more than a simple software package. It is a grouping of software systems all working together to provide the most accurate, relevant land surface characterization available. The additional software systems informing the AFWA-LIS modeling package include GEOPRECIP, CMORPH, and SNODEP. While each system and analysis (SNODEP, GEOPRECIP, CMORPH) is capable of providing independent output, the LIS system uses the products and blends them with additional observations through assimilation techniques, or through other data blending methods, to improve the representative snow and precipitation output. Therefore, it is more beneficial to consider the SNODEP, GEOPRECIP, and CMORPH analysis systems as components of the LIS modeling infrastructure.

The AFWA-LIS system ingests and blends weather data from a variety of sources to compute land surface products. The weather data include precipitation observations from remotely sensed gauge observations, snow depth observations, near surface temperature, humidity, wind observations, and cloud cover. The weather data are combined with background information, including soil type, land use, and related characterization.

One of the more critical parameters needed for accurate soil moisture analyses is precipitation, which LIS creates using information from several sources. The gauge observations, CMORPH blended multi-sensor precipitation estimates, and GEOPRECIP geostationary infrared precipitation analysis outputs are blended together internally in LIS using a Barnes weighting scheme and temperature threshold appropriate to respective data sources. Trends show passive microwave retrieval excelling for warmer terrestrial backgrounds and hydrometeor types (i.e., the blending of the datasets enables LIS to create the most accurate precipitation analysis possible using the strengths of each precipitation analysis method to help overcome weaknesses in the others.) Gauges are the best methods for analyzing precipitation; but the austere nature of military operating locations requires reliance on remotely sensed measurements and retrievals.

The LIS EnKF was added in 2006 to enable real-time assimilation of remotely sensed soil moisture observations. However, the EnKF system was implemented more generically, allowing it to assimilate other types of observations (i.e., snow, vegetation, surface temperature). This design feature has significant potential benefit to AFWA, including the opportunity to use AFWA global cloud analysis system-produced land surface field products (largely used as intermediate products within the cloud analysis system and include global IR skin temperatures and snow cover products) as assimilated products in LIS. The resulting improvements in LIS output would feed back through the gridded global skin temperature forecast produced with a combination of LIS analyses and GFS-forced LIS forecasts as a first guess field for the global cloud analysis. NASA is working to use the EnKF system with retrieved snow characteristics from microwave and visible radiometer sensors to improve the snow products that LIS generates with the help of the SNODEP model. The EnKF system will also be exploited in blending precipitation observations and analyses.

An interface between LIS and the CRTM was created to enable two-way interaction between the two modeling systems. LIS can support satellite radiance assimilation by CRTM, and CRTM can be used to enable radiance assimilation in LIS.

The Land surface Verification Toolkit (LVT) (Kumar et al. 2012) was developed to enable extensive verification and validation of LIS products while facilitating data assimilation and ensemble modeling development efforts. The LVT system uses observation types from a variety of platforms (satellites, gauges, multi-sensor analysis products) to verify LIS output and to compute skill metrics as well as statistics useful for improving data assimilation and ensemble-based approaches such as uncertainty estimation (Fig. 2).

Figure 2. Land surface Verification Toolkit (LVT).

3.2 End-state goals

Both near- and long-term development goals are necessary for an end-state modeling system capable of delivering advanced terrestrial numerical weather predictions. The system needs to deliver advanced, tailored products capable of broadening weather support to DoD and IC. Near-term goals include both infrastructure and product integration and development, while long-term goals are focused on fielding new output variables and product capabilities.

The first LIS development plan focused on improving precipitation analyses, integrating the ensemble Kalman Filter, and creating a link between LIS and the CRTM. This enabled LIS to assimilate satellite-based land surface properties (soil moisture, soil temperature); to support satellite radiance assimilation, both in LIS and in atmospheric forecasts models through the linkages available between LIS and CRTM; and to create a fully-coupled land-atmosphere earth analysis and prediction system through a coupled LIS-WRF system. The first LDP was developed during the period in which AFWA was preparing for the since-cancelled National Polar-orbiting Operational Environmental Satellite System (NPOESS) program series of satellites. While the advances in LIS infrastructure delivered a highly robust modeling architecture with a number of capabilities, the “operators” necessary to take advantage of the LIS capabilities had not been fully developed. The focus for the next phase of LIS development will transition to expand the types of products LIS is capable of supporting while concurrently maturing the infrastructure. This will allow an increase in the types and amount of remotely-sensed data used in research and in operational organizations to create land surface analysis and forecast products. This focus will continue to solidify the ability for the LIS software to deliver the most accurate soil moisture analyses and forecasts possible while also delivering new products that will expand support opportunities into areas currently underserved by the DoD weather communities.

Currently, LIS creates land surface products (soil moisture, soil temperature, heat flux, and canopy vegetation health) that are largely “intermediate,” meaning the products are used as input parameters to cloud detection algorithms, mobility models, target decision algorithms, or modeling and decision support algorithms to create derivative products. As a result, LIS’s importance to warfighter support can be undervalued. One should note that soil moisture and snow depth are products fundamental to a broad range of military and national security organizations. Therefore, the focus of the next several years in LIS-related research and development is aimed at delivering new or improved Army, Air Force, and Intelligence "weather" products capable of delivering accurate environmental intelligence for battlefield surveillance, awareness, and planning across the full spectrum of traditional and non-traditional military activities. This focus shift will increase weather support for a broad range of military activities, with a special focus on humanitarian response, special operations forces, and Army stability operations missions.

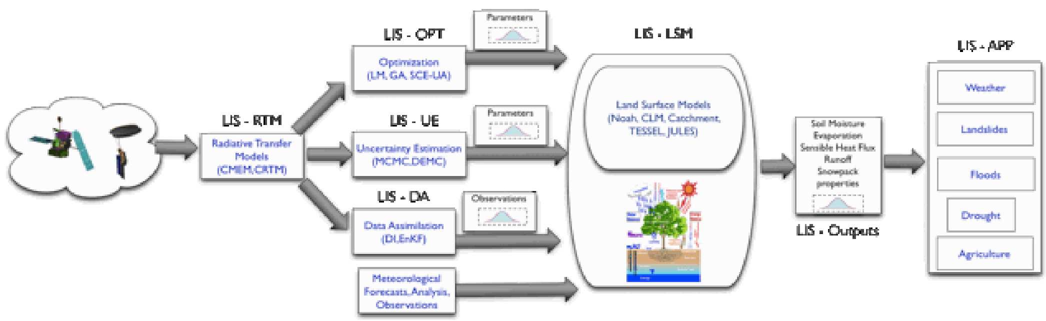

Figure 3. LIS development goals.

The NASA team has created an illustration (Fig. 3) that describes the future LIS framework, breaking out each processing component into modular, configurable components that can be enabled or disabled based on the needs of the user or the product. The LIS-RTM component contains the radiative transfer models that will enable future satellite radiance assimilation and will better characterize radiative fluxes. The LIS-OPT, LIS-UE, and LIS-DA modules make up the data assimilation and observation "handling" components. The plethora of integrated land surface models are contained and described within the LIS-LSM. The LIS application subsystem (LIS-APP) contains linkages to end-use application models (such as landslide forecasting and mobility assessment models). LVT, in addition to performing systematic model verification and evaluation, will also generate a variety of products that are either directly used for decision support or are integrated into other decision support algorithms. For example, the land surface model outputs from LIS are processed by LVT and generate a suite of standardized drought indices, such as the standardized precipitation index (SPI), standardized runoff index (SRI), standardized soil water index (SSWI), percentiles and anomalies relative to climatology, etc.

The development of the LIS-RTM, LIS-DA, and LIS-APP modules and LVT will be the primary focus during the next five to seven years. Many of the components developed during the first 5 years will continue to receive attention at reduced levels. This includes improving precipitation analysis, integrating new, finer scale land surface models; improving the accuracy of meteorological observations; and incorporating new physics that account for surface water storage (lakes, wetlands, gaciated regions) and urban environments. This support stems from the need to incorporate new product capabilities, to develop physical "observation operators" for satellite radiance assimilation, and to improve the physical outputs used in derivative products. However, to effectively bridge the gap between weather and military utility, the primary goals need to focus on expanding development of terrestrial and terrain-affected military products that support military planning and scenario systems.

3.3 LIS use cases

The most visible use cases for LIS output are support to military mobility, to austere entry, and to remote airfield construction. Mobility includes both mounted (vehicle-based) and dismounted (on-foot) maneuver support. AFWA's historical support to these three categories of military operations has been limited by the availability of high resolution (at or finer than 1 km) soil moisture data. However, the LIS system enables AFWA to begin supporting such capabilities. ERDC recently demonstrated initial prototype opportunities for using AFWA data (LIS, SNODEP products) output to initialize real-time and "climatological" mobility computations. Two of the examples include a study for the USAF Space Based Environmental Monitoring Analysis of Alternatives for the Weather Satellite Follow-on program and a maneuver operations planning study for Marine Corp Intelligence Activity concerning the Arc-of-Instability (see Fig. 5) conducted by ERDC. In 2008, ERDC obtained LIS-produced soil moisture output for Afghanistan at 1-km scale and developed software to feed this information into the USACE NATO Reference Mobility Model (NRMM) based Standard Mobility (STNDMob) application (Fig. 4) (Baylot et al. 2005). This initial demonstration project used AFWA (16th Weather Squadron) LIS output to generate a vehicle speed map for different military ground vehicles for a region in Afghanistan at 1-km scale.

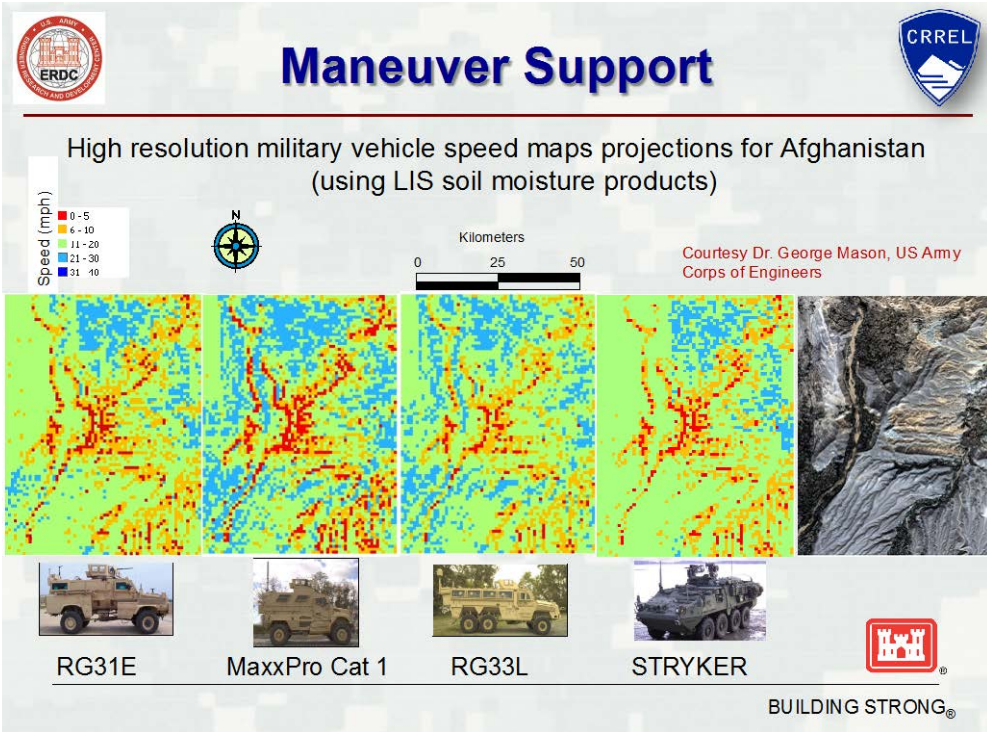

Figure 4. Results from NRMM-based Standard Mobility Application for four different vehicle types using LIS soil moisture products to compute the soil strength.

Additionally, CRREL used the operational LIS configuration in a retrospective case study to compute six-years worth of 1-km LIS output for eight large domains covering regions know as the "Arc of Instability" (Fig. 5). The ERDC Geotechnical and Structures Laboratory (GSL) processed the LIS output and mined the data for the wettest and driest periods in the data cube. They then computed vehicle speeds for those cases, along with go/no-go probabilities for many different classes of ground vehicles, for a number of smaller regions within the eight LIS domains. This project effectively demonstrated the utility of including LIS as another elemental model within the Environmental Data Cube Scenario Simulator (EDCSS).

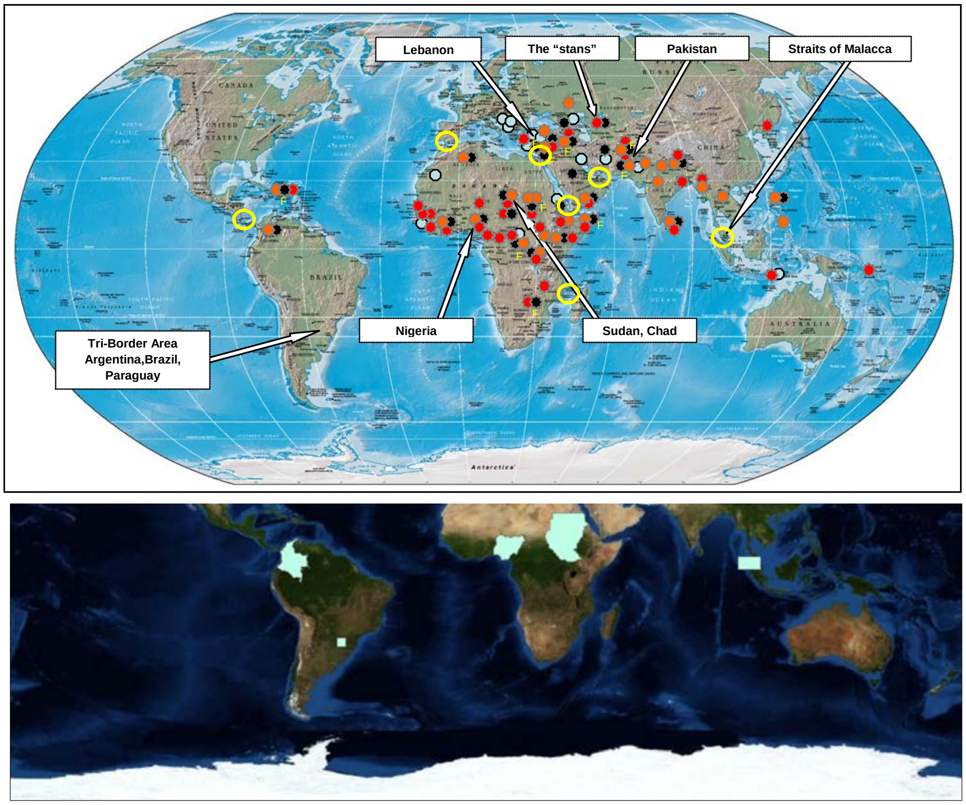

Figure 5. Map showing the Arc of Instability (top) and the regions included in the ERDC mobility study (bottom).

3.3.1 Support to hydrologic and hydraulic analysis and prediction

While the Army is responsible for delivering military hydrology and hydraulic support, weather input is critical to developing effective products to support rapid and accurate decision-making. At AFWA, LIS is an important terrestrial weather modeling system that will enable real-time, decision-ready hydrologic forecasting for ground forces, supporting river crossings, river height estimates, flash flood predictions, and similar needs. Also, using LIS to initialize higher resolution Army modeling products will drive additional research into scaling caused by resolution differences of LIS output and Army modeling capabilities and requirements.

Critical LIS products supporting hydrology include precipitation analyses; snow cover, snow depth, and snow water analyses; and soil moisture analyses. The accuracy of the precipitation analysis is very important for hydrologic analysis and prediction. A recent study completed by Eylander et al. (2012), using LIS to initialize a USACE watershed hydrology model, highlights the importance of precipitation analyses for predicting resulting hydraulic flow. In the study, Eylander et al. added error to the LIS precipitation products at 5% increments up to ±30%. When evaluating the streamflow output from the USACE Gridded Surface and Subsurface Hydrologic Analysis (GSSHA) model, Eylander et al. found that the resulting error in the instantaneous streamflow rate nearly tripled when the LIS precipitation output underestimated precipitation. Errors in the long term "accumulated" or seasonal flow values were half the error values measured in the precipitation analysis (Fig. 6 and 7). These results highlight the criticality of accurately analyzing precipitation.

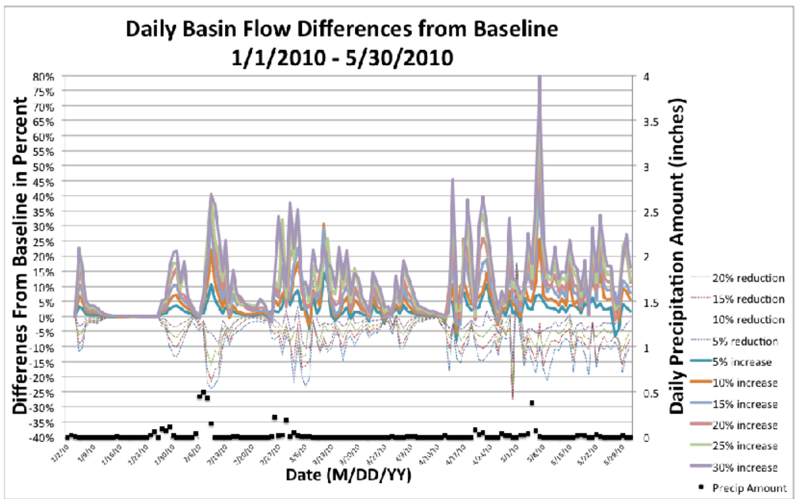

Figure 6. Daily percentile differences in the water basin flow rates for an Afghanistan watershed based on the precipitation analysis error increments. Solid lines included positive errors (precipitation added to the LIS analysis in 5% increments) while dashed lines are for negative error increments. The black dotted line represents the daily precipitation amount in inches.

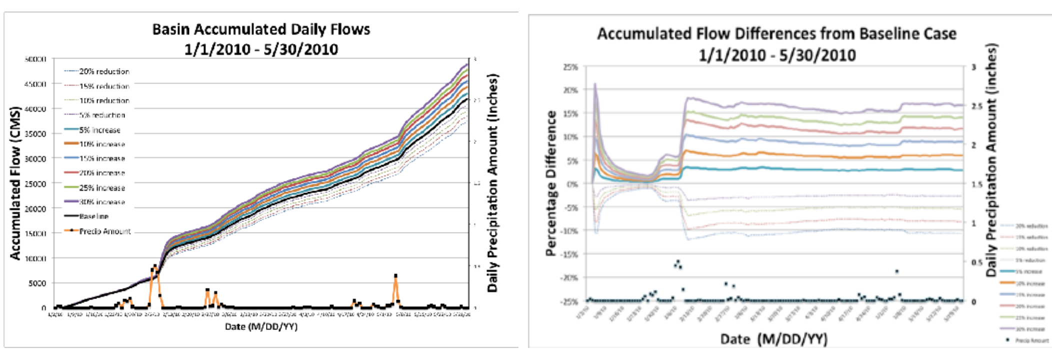

Figure 7. Accumulated daily flow rate (left) and percentage differences (right) in the water basin flow rates for an Afghanistan watershed based on the precipitation analysis error increments. Solid lines included positive errors (precipitation added to the LIS analysis in 5% increments) while dashed lines are for negative error increments. The black dotted line represents the daily precipitation amount in inches.

3.3.2 Precipitation analyses

Precipitation is one of the most critical and widely used products in the LIS system. The US Department of Agriculture uses the precipitation analysis to support economic policy decisions, intelligence agencies use it to analyze environmental interactions with global security operations, and Army groups use this analysis to predict hydrology and mobility. The internal precipitation analysis, generated by combining multiple observation sources, is also critical to accurately assessing soil moisture and snow depth. Because it is critical to both internal LIS computations and external use, computing a highly accurate precipitation analysis has long been a focus for LIS development.

3.3.3 Numerical weather prediction (NWP) model initialization

Output from LIS initializes NWP system land surface variables. AFWA operates LIS to support the Weather Research and Forecasting (WRF) NWP model lower boundary condition initialization, while the National Weather Service (NWS) National Center for Environmental Prediction (NCEP) is using LIS to initialize the land variables in their NWP systems, including the Global Forecast System (GFS) and, in the near future, the North American Mesoscale (NAM) model. The NWP systems depend on internal land surface models to calculate the surface energy budget, snow depth, and other factors important thermodynamically to numerical weather prediction. The LIS provides the initial land surface products (soil moisture, soil temperature, and snow depth) used to initialize the same parameters in the NWP models.

Accurate assessments of soil moisture, skin temperature, and vegetation conditions will become increasingly important with the increased reliance on satellite remote sensing of the atmosphere, especially over land areas. Current atmospheric remote sensing capabilities are limited over land areas due to difficulties in separating surface emissivities in both the infrared and microwave portions of the spectrum. The ability to analyze and to predict the surface background microwave emissivities is important to enable an increased number of over-land satellite observations usable in a NWP data assimilation system. This focus area will become an area of significant focus for atmospheric data assimilation over the next 10 years.

3.3.4 Imagery analysis and scene simulation modeling for planning, war gaming, and intelligence gathering

Generating an accurate assessment of battlefield conditions for pre-mission planning, on-the-fly decision-making, and generating war gaming scenarios is an area of active research within the US Army. CRREL is using soil moisture and surface temperature products to initialize scene simulation models that will support ground forces with optimal sensor placement. Forces can place these sensors within a combat outpost, on ground vehicles, or on individual soldiers to support the detection and identification of non-friendly forces during an engagement. This will also increase friendly forces' ability to effectively remain undetectable and unidentifiable. The critical parameters supporting imagery analysis and scene simulation include soil moisture, surface temperatures, surface winds, surface topography information, soil strength, and vegetation characterization. Accurate understanding of surface features is also important for intelligence gathering activities.

In addition to the scene simulation models, several groups are working collaboratively to develop a joint atmospheric and terrestrial "weather cube" in the Environmental Data Cube Support System (EDCSS). Expanding the EDCSS capability to include advanced surface characterization supports a variety of Army and Intelligence Community needs, including synthetic scene generation and military scenarios simulation within DoD modeling and simulation programs. The DoD Modeling and Simulation Coordination Office supports the EDCSS system.

3.3.5 Target acquisition and identification

Accurate remote identification of potential targets and sensor acquisition for target lock-on requires a detailed understanding of the target and surrounding environment. For targets located on the ground, this includes knowledge of the surrounding scene to detect camouflaged targets. As the atmosphere warms and cools, targets will generally respond, depending on their physical characteristics. During portions of the day, the target achieves a temperature equal to that of the background, termed the crossover temperature. Mission planners use this information to determine the best times to acquire targets.

4 Near Term Goals

Each year of the development plan includes three segments representing goals for NASA, AFWA, and ERDC-CRREL. The goals do not consider the funding necessary to accomplish specific tasks; rather, they identify goal ownership and responsibility for developing a specific task breakdown necessary to achieve the long-term goals stated in the plan. The availability of funds on a year-to-year basis and the ability to cost share between organizations will dictate the accomplishment. ERDC-lead efforts may involve collaboration with Army Research Lab; other ERDC laboratories (e.g. GSL, CHL); NASA Goddard; or other government, corporate, or university-based research centers.

4.1 FY13 development

4.1.1 CRREL lead research and development

4.1.1.1 Army Fast All Season Soil Strength (FASST) model baseline integration and benchmarking within LIS

The US Army FASST model (Frankenstein and Keonig 2004) is a complex land surface model developed by the Army to predict soil strength for military maneuver support. The model is used as a component of several Army decision support systems currently in the development phase, such as the Battlefield Terrain Reasoning and Awareness (BTRA) system and now the Geospatially-Enabled Multi-modal Situational Awareness toolset in development within ERDC. While the FASST model has been a component of Army geospatial applications, there lacks a consistent plan for integrating "weather." Recently, the discussion has moved toward integrating FASST as a component of the weather "production" process as the driver (initialization) for higher resolution versions of the model run in geospatial applications or as the method for providing soil moisture and soil strength directly to Army programs requiring such information.

In 2011, the NASA LIS team used Army funds to successfully integrate the FASST LSM into the LIS baseline. However, the existing version of FASST is capable of operating only on very high resolution, very limited domain size areas using ERDC analyst-generated background information (terrain categorization). These data can be difficult to obtain. In FY13, CRREL and NASA will collaborate to modify FASST to operate from remotely sensed, gridded, worldwide terrain categorizations used by the other LSM's currently in LIS, as well as perform a benchmark test on the FASST output. The results of this work will be a version of FASST, in LIS, that will be able to operate on both "weather" and "Army" scales using a more universal input data set.

4.1.1.2 Integration of NGA provided higher resolution soils information into LIS

The National Geospatial-Intelligence Agency (NGA) recently supplied CRREL staff with a new, higher resolution (and potentially more accurate) global map of world soils information used as a basis for the physical computations of soil strength and soil-water interactions. The delivered data are available at a 1-km global resolution—a substantial improvement over the currently used United Nations Food and Agriculture Organization (FAO) global 5-km datasets typically used in global land data assimilation systems (and in the current version of LIS). Additionally, NGA has promised a regional, 100-m resolution dataset that would enable higher resolution, large domain, grid-based soil moisture and soil strength modeling from LIS. CRREL will be collaborating with NASA to integrate the new datasets into the LIS software baseline.

4.1.1.3 Research the capability of LIS to support water security related topics

The *February 2010 Quadrennial Defense Review* included new language for topics related to "stability operations" and "building partner capacity." The goals are to identify, prevent, and deter conflict. The IC has expressed significant interest in monitoring international hydrology as a predictor of conflict. CRREL and NASA are collaborating to develop a global drought prediction tool supporting intelligence organizations. The LIS-based tool will use a climate forecast model to predict seasonal climate anomalies. The goal is to create a regional and global forecast of where water and food security may be at risk, to prepare DoD for potential humanitarian assistance missions, or to provide regional force protection where US troops may be threatened by drought or flooding. While seasonal predictions are not a current product AFWA supports, a seasonal prediction system at AFWA supporting IC and DoD humanitarian response planning requirements is important to consider with support from the 16th or 14th Weather Squadrons.

CRREL and NASA are collaborating to investigate this new seasonal prediction option using LIS combined a seasonal prediction forecast model. This NGA-funded investigation also researches linkages between drought and regional security.

4.1.1.4 Increased support toward Army capabilities (maneuver support and military hydrology)

Army and Marine organizations have expressed interest in gaining an ability to support real-time automated route planning, gap crossing, and water routing products for force protection and base defense. For instance, CRREL is interested in building linkages between basic LIS outputs (soil moisture, precipitation, etc.) and Army models to explore the development of machine-to-machine decision support systems for mobility analyses, remote opportune airfield detection, hydrologic analyses supporting military planning, and other needs. Additionally, CRREL is interested in using WRF model output to explore the potential for predictive-based capabilities. This is a greatly underserved area in the austere environments in which DoD typically operates. The ERDC Coastal and Hydraulic Laboratory (CHL) currently uses complex hydrologic and hydraulic models to predict streamflow; however, the modeling system is not rapidly relocatable because, to provide accurate estimates, CHL staff need to calibrate and tune each individual water basin separately against ground observations. Additionally, the products supplied by CHL are more tuned toward analyses than predictions. CRREL and CHL are interested in working together, using LIS and WRF model baselines. The goal of a joint agency research and development program would be to develop a scalable solution that would allow for rapid reactions to flash flooding while also providing accurate risk-based assessments of flooding and flash flooding in data-poor or data-denied regions.

4.1.1.5 Development of downscaling technologies to bridge physical gaps between "weather" scale and "army" scale

There continues to be a significant divide between "weather" resolution and "Army" scale. Traditional Numerical Weather Prediction (NWP) output available from AFWA, at horizontal scales greater than 1 km, is considerably coarser than what the Army considers relevant for use in operations. Because of the scale differences, it has been relatively difficult to apply AFWA data to high-resolution Army decision support systems until recently. Over the past several years, WRF and LIS have been outputting predicted weather products with increasingly higher resolution. AFWA and ERDC groups have been able to successfully demonstrate prototype products that can be used to support mobility and hydrologic analyses. Additional work needs to be done to improve downscaling capabilities within LIS and to develop new technology that can effectively bridge the gap between weather scale and Army scale. CRREL is supporting research in this area using the DoD Small Business for Innovative Research (SBIR) topics in the FY12.2 topic announcement. CRREL successfully staffed a “downscaling” topic in 2012, which became part of the 12.2 announcements, with a goal of developing a method to downscale LIS soil moisture output to higher resolutions more applicable to Army scale needs. CRREL is managing the SIBR project with a goal of completion in FY15.

Continued development of downscaling methodologies, advancement of the FASST LSM within LIS, and development of ensemble capabilities will greatly enhance the military’s ability to support real-time tools for analysis and prediction of mobility, maneuverability, and austere entry.

4.1.2 AFWA sponsored research and development at NASA

4.1.2.1 Snow assimilation capability

The accurate and precise analysis of snow and snow water content for DoD operations is a weak point in AFWA operations, leaving operational customers to scavenge for a fractured support from defense laboratories and other national agencies. Additionally, the types of products available are not directly suitable for supporting DoD missions of maneuver support, intelligence gathering, route security, and other similar requirements. The ability to generate a high resolution, accurate portrayal of snow and snow water storage is very difficult because of the lack of in situ observation and the difficulty in measuring snow from space. AFWA and other organizations have used two of the best methods for measuring snow from space, capturing snow cover extent from visible radiometers and snow water content from microwave radiometers, to create maps of snow depth and snow cover; however, the resolution of the snow depth and snow water content at 25 km or more, is much too coarse to directly support ground operations. Previously, AFWA supported NASA development of a satellite data blending technique with the AFWA-NASA Snow Algorithm (ANSA) (Foster et al. 2011) that combined NASA MODIS snow cover maps with AMSR-E snow water content maps to create a 5-km horizontal resolution map of snow coverage and depth. However, AFWA’s difficulties in obtaining and processing MODIS data combined with the recent demise of the AMSR-E sensor resulted in difficulties in implementing the new algorithm in the snow depth analysis software. A better strategy may be to take advantage of initial investigations completed by NASA to assimilate snow information into LIS to create high resolution maps of snow cover, snow water content, snow depth, and resulting hydrological products (to include post-products developed by ERDC). To accomplish this work, NASA needs to consider adding advanced snow physics algorithms and satellite-based data assimilation advances to LIS that take advantage of both model and remote sensing techniques while incorporating model and observation uncertainties.

4.1.2.2 Ensemble modeling development

A primary goal for near-term infrastructure advancement is to continue developing ensemble modeling. An ensemble modeling capability is critical to future ground operations, primarily because of the large number of unknowns and parameterized variables necessary for terrestrial modeling. The surface energy balance values, along with soil moisture and temperature values, are computed using primarily weather as a “forcing” value, driving land surface physical models. The land surface models, which are components of both LIS and WRF, contain many arrays of parameter values, such as soil and vegetation types, surface albedo, and emissivity. In FY12, NASA began developing a parameter perturbation capability, enabling the computation of an ensemble spread for some output variables. This initial development focused on uncertainty characterization for soil moisture and soil temperature variables, primarily to support point-based analyses of atmospheric and surface profiles. Expanding on ensemble modeling and uncertainty characterization is still necessary to generate risk-based products to supply data for high resolution military capabilities, including maneuver support, austere entry, and soil strength. Even with the increasingly sophisticated capabilities in LIS, the AFWA-LIS products will generally be available at weather scales (resolutions of 1 km or coarser), yet military operations generally take place at field scale (or finer) and require higher resolution output. Accounting for the potential variability in background surface types within the coarser resolution, LIS output is necessary to initialize higher resolution user applications that will be running at field scale or finer. Additional risk-based ensemble products should be developed during this period, such as risk-based soil strength forecasts, using the FASST model in LIS.

4.1.2.3 Noah-MP integration and testing

NCAR is testing a new version of the Community Noah LSM, named Noah-MP (multiphysics). The new version of the model is considerably different in both architecture and capabilities. NASA has obtained the new model and incorporated it into the LIS framework; however, extended testing is necessary to fully evaluate all the options available and the effects on and tradeoffs with respect to LIS output. This extended benchmarking period should be a joint effort with NCAR and NOAA's National Center for Environmental Prediction land modeling team. AFWA, NASA, NCAR, and NCEP are major partners on the Noah working group.

4.1.3 AFWA integration and testing

It is necessary to fully test and integrate the many additional, unused capabilities of the current version of LIS in the AFWA software repository and production system to fully realize LIS goals. Two of the more significant unrealized LIS improvements are the data assimilation and coupled LIS-WRF capabilities. Additionally, AFWA has yet to explore multi-model options available within the LIS software from an ensemble perspective. The following projects are a prioritized listing of integration efforts to implement capabilities developed under the previous LIS Development Plan.

4.1.3.1 Evaluate multi-model-based products (catchment, Noah-MP, FASST)

The operational AFWA LDAS has used the Noah LSM since the early days of land surface modeling within the agency. While the Noah LSM is considered a "benchmark" LSM within the hydrometeorological modeling community, there are many additional LSMs with strengths and weaknesses, as compared to the Noah LSM, that should be considered for optional use to benefit an ensemble capability or to support additional product development. For instance, the NASA catchment LSM offers support for catchment-based terrestrial water storage (groundwater), a capability the current Noah LSM does not support. The Army Fast All Season Soil Strength (FASST) model offers a capability to diagnose soil strength for Army mobility computations. The new Noah Multi-Physics (Noah-MP) model provides a significantly enhanced vegetation and snow cover modeling capability over heritage Noah LSM physics. Each of these LSMs, and possibly others, offer advantages for running operationally at AFWA as either part of an ensemble or for specialized support products. For AFWA to execute a number of models, each of the models needs to be tested with the AFWA-specific weather forcings; and the output needs to be validated and compared with others LSMs. Additionally, it is necessary to consider new methods of combining multi-model output together through averaging or weighting. While the ensemble balancing or weighting effort is more than a single-year task, the initial development of a multi-model capability needs to begin with an initial goal of establishing a much larger future operational capability that can better support military operational risk-based decision making.

4.1.3.2 LIS-CDFSII testing as a replacement for SFCTMP

Soon after the Ensemble Kalman Filter (EnKF) was incorporated into the LIS framework, Reichle et al. (2010) successfully demonstrated a capability to assimilate surface skin temperature measurements into LIS from geostationary sources. This was a prototype demonstration for a similar Cloud Depiction and Forecast System Version II (CDFS-II) and LIS configuration. This assimilation would allow LIS to support the CDFS-II system with the necessary skin temperature forecasts needed to drive cloud detection and identification via IR frequency.

A goal from the first LIS development plan was to replace the AFWA Surface Temperature (SFCTMP) model with a LIS-based capability for providing surface skin temperature forecasts necessary for IR frequency cloud detection. Previous LIS infrastructure development, including the ensemble Kalman filter, has the capability to assimilated satellite surface skin temperature data and the integration of a two-stream, four-stream, and correlated-k radiation algorithm supporting higher resolution radiation computations from pixel-level cloud optical properties. This supports a close tie between the CDFS-II system and LIS. Additionally, the SFCTMP analysis possesses a significant stair-step bias that shifts from very low bias to a very high bias in a relatively short time period (days) while the error profile for LIS-based skin temperatures appears more steady (skin temperature assimilation not included). The improved error profiles and the new capabilities added to LIS (i.e., skin temperature assimilation) should improve cloud analyses and be considered for operations while removing a legacy, poorly understood, and somewhat heuristic analysis (SFCTMP) from operations.

4.1.3.3 WindSAT or AMSR2-based SWE and soil moisture assimilation

The recent loss of the NASA Advanced Scanning Microwave Radiometer for the Earth Observing System (AMSR-E) sensor was critical in that it was the only microwave radiometer data AFWA received that had a 10-GHz frequency for the measurement of deep snow. The WindSAT sensor flying on the Coriolis satellite has a 10-GHz frequency for the measurement of deeper snow and also contains a 6-GHz frequency for the measurement of near surface soil moisture. Additionally, the Japanese Space Agency is flying a new AMSR-E-like sensor, AMSR2, on the GCOM-W satellite; and the data will be available sometime during 2013.

Kumar et al. (2009) already demonstrated several prototypes to assimilate space-based soil moisture observations in LIS. The demonstration of the capability to assimilate both Advanced Microwave Scanning Radiometer for the Earth Observing System (AMSR-E) observations and WindSAT soil moisture observations into LIS demonstrated significantly improved soil moisture analyses over those computed from only weather and precipitation forcings. At issue is not whether assimilating soil moisture provides a benefit, rather it is the availability of space-based soil moisture observations, the ability to process the data at AFWA, and the availability of algorithms to compute snow water content and soil moisture on a world wide basis. Space-based soil moisture observations with large fields of view have been limited to microwave imagers with 6-GHz frequencies. With the dissolution of the National Polar-orbiting Operational Environmental Satellite System (NPOESS) program, and subsequent defunding of the Defense Weather Satellite System, there are no current plans to fly a Microwave Imager/Sounder class of instrument with a 6-GHz frequency. However, with the recent failure of AMSR-E and given the age of WindSAT, it is important to find newer sources of space-based soil moisture observations. The European Space Agency is currently flying the Soil Moisture and Ocean Salinity (SMOS) sensor, an L-band (1.4-GHz) frequency polarized instrument that measures, among other parameters, soil moisture at a resolution of 35 km.

4.1.3.4 Real Time GVF

Incorporating remotely sensed vegetation products will lead to improved surface analyses of skin temperature and energy budgets. Work by AFWA, collaboratively with NCAR, has shown that including MODIS-based vegetation “greenness” improves the diagnosis of surface and ground heat flux variables within the LSM, especially during "green-up" and anomalous climatic conditions (drought). In one example, rapid green-up of vegetation in the southeast US—more rapid than climatology would predict—resulted in significant differences in the LIS surface heat flux variables.

4.1.3.5 Advanced Scanning Microwave Radiometer 2 (AMSR2) integration

The AMSR2 sensor, flying on board the Japanese space agency GCOM-W satellite launched in 2012, is the next sensor in the AMSR-series of passive microwave radiometers resulting from the NASA-JAXA partnership. The data from AMSR2 should be ingested by AFWA and made available for use in the Snow Depth Analysis (SNODEP) component of the LIS infrastructure. The AMSR series of PM instruments are improved over the US DoD series of PM sensors known as the Special Sensor Microwave Imager/Sounders (SSMI/S) because of the inclusion of 10-GHz and 6-GHz frequencies. The 10-GHz frequency is beneficial in measuring deeper snow packs, versus PM sensors, such as SSMI/S, that use only 19-GHz and 37-GHz frequencies; and the-6 GHz frequency is suited for measuring soil moisture. Initially, testing and integration of AMSR2 data into the snow analysis components will provide immediate impact. AFWA needs to explore testing of soil moisture observations as well.

4.2 FY14 developments multi-model ensemble products

4.2.1 CRREL lead research and development

4.2.1.1 Brownout prediction

The ability to accurately predict the potential for brownouts to disrupt operations is highly limited. Accurately predicting dust lofting is difficult because of complexities involved in modeling the coupled land-atmosphere. Dust lofting potential products, which aim to use probabilities for dust storm occurrence, require high resolution maps of dust source regions, soil types, and vegetation. This calls for new model-based prediction methodologies to better predict the soil lofting potential on both large and small scales. This is no trivial task with the difficulty increasing as the scale moves to finer resolutions. CRREL needs to lead development of a combined weather and terrestrial modeling capability that would provide support to both large- and small-scale dust events, including support to rotary-wing induced events.

4.2.1.2 Maneuver support

The ability to produce automated, high-resolution, weather-impacted analyses and predictions of vehicle speeds for different weight classes and to generate weather-impacted vehicle route planning and dismounted mobility plans would be a significant capability to support a broad spectrum of military operations. The Army is sponsoring research aimed at creating geospatial applications to obtain weather, terrain, and geospatial information for mobility. The goal of this research area is to better link AFWA provided weather information to the ERDC maneuver support research areas, to increase AFWA's technical capabilities and knowledge base to support Army mobility, to and develop linkages between LIS and WRF output with Army mobility applications. Additionally, AFWA and ERDC should evaluate possible integration of weather-affected mobility applications in the AF Weather Webs (AFWEBS).

4.2.1.3 Military hydrology

A major concern for base defense, force protection, and humanitarian assistance is the lack of flood and flash flood predictions in most of the regions where DoD is involved. In the US, a combination of agencies and products provide hydrometeorological predictions that support heavy rainfall, flooding, and flash flood predictions. However, no such cooperation or product offering exists in theater, where the DoD often deploys significant numbers of troops and equipment. Army units need the ability to provide a priori knowledge of force protection in a variety of water scenarios, from river crossing to weather-induced flash flooding. Currently, AFWA provides predictions of precipitation; and operational weather squadrons are responsible for providing excessive rainfall predictions. There is no operational hydrometeorological prediction model that supports flooding or flash flooding. ERDC uses a variety of tools to support basin and watershed-level hydrology analyses, yet no theater-level rapid-response capability exists. The development of a rapid response flooding forecasting and frequency analysis capability, using the coupled LIS-WRF system, is necessary outside the US in regions where the DoD has significant interests or where the IC is monitoring.

4.2.1.4 LIS-based snow products

The CRREL team is currently evaluating the LIS-based snow products and comparing them to current data used to create operational snow products.

A future LIS-based snow assimilation capability provides significant promise for creating a more accurate and precise snow cover and snow depth analysis supporting military hydrology, mobility, and other derivative capabilities. CRREL's operational snow products, based on DMSP Special Sensor Microwave Imager/Sounder (SSMI/S) snow water equivalent data, are used to infer hydrologic information based on comparison with climate. To drive towards higher resolution, CRREL should evaluate an assimilation-based approach using the high-resolution terrain characterization in LIS to effectively downscale the coarse resolution satellite information. Evaluating LIS as the source of information to create new products and beginning to transition to LIS-based products will enable future technology transition of CRREL capabilities to AFWA.

4.2.1.5 Drought prediction

CRREL and NASA will continue to evaluate and develop a capability to predict future drought conditions worldwide to support future Army programs in stability operations and to support IC interests. A fully mature drought prediction capability should embrace ensemble-based capabilities and deliver products able to support and inform stability operations and the intelligence community, which is significantly more complex than simply producing a prediction of drought or no-drought. Research into drought effects on socio-cultural and socio-economic security and developing products that can predict population impacts will be a significant focus. The ultimate goal in a national-security focused drought prediction capability is be to develop products that support remote monitoring of regional stability with the goal of providing early-warning situational awareness of destabilizations that may result in the need for military operations or humanitarian support.

4.2.1.6 Coupled LIS-WRF testing, evaluation, and prototyping

NASA and NCAR collaborated to develop a coupled version of LIS and WRF in 2008–2009; however, the fully coupled LIS-WRF system never received significant support from AFWA owing to the complexities involved in operating such a system. The perception is that the cost-factor in operating a coupled LIS-WRF system outweighs the benefits. The primary reason for this perception is a lack of sufficient test and evaluation of the coupled system. Additionally, the Earth System Modeling Framework (ESMF) that was initially used as the method to couple LIS and WRF created additional complexities that would not have been sustainable from a maintenance standpoint. The new coupling mechanism is much simpler; essentially, it involves a single subroutine that replaces a call to a land surface model with a call to LIS. The subroutine was written and is maintained by NASA. This simpler coupling should be sustainable and maintainable over the long term until WRF is replaced with a new modeling infrastructure; it should also be simpler to operate. It is important to test this infrastructure to evaluate the benefits that a coupled LIS-WRF system offers. CRREL plans to field a coupled system on an Army computing system to build prototype products supporting Army-specific capabilities that a non-coupled system would be unable to support, including products supporting military hydrology, mobility, and other evolving requirements.

4.2.2 AFWA funded R&D at NASA

4.2.2.1 Ensemble development, ensemble weighting

A mature ensemble modeling system should ideally have the capability to operate in a single-model, parameter-perturbation mode and with a multiple model operation mode to enable multiple physical models to fully account for the uncertainties in soil moisture modeling. Improving the parameter estimation, error propagation, and uncertainty estimation capabilities of LIS are important to developing a single-model ensemble capability. Additionally, expanding the number of members in an ensemble tends to broaden the uncertainty without necessarily gaining forecast skill. To increase forecast skill, it is necessary to account for the weighting of the ensemble output, based on a full evaluation (to include benchmarking and validation) of the configurations to reduce the uncertainty around observations. To this end, development of an ensemble soil-modeling system should begin to focus on the use of multiple models and member weighting. The output from an ensemble approach, coupled with Army modeling systems, will enable risk-based, decision-grade products.

4.2.2.2 LIS-APP and Land Verification Toolkit development

The LIS applications (LIS-APP) subsystem and LVT subsystem is ideally suited for housing software and algorithms to deliver new products, including hydrologic, drought, vegetation health, and many other possibilities. As new drought and hydrologic products are developed, NASA should expand the LIS-APP to include the new algorithms or models that do not require feedback during the core LIS model cycle to create products. This would include water quality, soil strength, and other similar products. The

LVT systems' continued development will enable further post-processing and calibration of hydrologic products requiring feedback.

4.2.3 AFWA Integration

4.2.3.1 Noah-MP parallel operations

The Noah-MP LSM could present a significant challenge for AFWA given the significant changes in the physics package. AFWA should dedicate considerable time to testing the many new Noah-MP options available, using the many new options available in the LIS framework (e.g., LVT) and evaluating which options best support both the offline analysis and the initialization of WRF. An extended testing of Noah-MP is possible in the LIS testbed that has archived multiple years of data for this purpose. However, once testing is complete, parallel operations in AFWA's operational system may need to be conducted either on a development system or in a production environment to enable users to transition to a Noah-MP-based LIS output.

4.2.3.2 Multi-parameterization ensemble modeling to support PAIS.

AFWA integration of a LIS-based ensemble land surface analysis system is important for future risk-based support to Army and the intelligence community. Currently, the IC has issued requirements necessitating uncertainty estimates for surface parameters delivered as part of the Point Analysis System (PAIS) for soil moisture, temperature, snow depth, and a variety of other variables. Additionally, uncertainties are important for Army support. NASA's development of a parameter perturbation-based initial ensemble capability should be ready for initial testing in FY14. The establishment of a LIS-based ensemble land surface analysis system will require considerable testing and evaluation, and new product development will need time to mature to take full advantage of the ensemble products. The fielding of a LIS-ensemble on the development and test system at AFWA is the first step in that process.

4.2.3.3 AMSR-2 soil moisture and SWE assimilation

Beyond the initial work to integrate AMSR2 snow products into the AFWA's snow analysis processing, AFWA needs to test and evaluate the NASA-developed SWE capability as a way to fully replace the separate snow-depth processing algorithms. The goal of an assimilation-based snow-product system is to enable more accurate, higher resolution, LIS-based products that better account for terrain, ground temperature, and snow age in generating a snow depth product and to improve the diagnosis of snow water storage for the spring melt season and the handling of snow melt.

4.3 FY15 development

4.3.1 CRREL efforts

The research and development CRREL begins in FY14 will continue through FY15 and FY16 with a focus on supporting the development of a brownout prediction capability, developing a machine-to-machine maneuver support capability, supporting the development of a domain-wide military hydrology prediction capability, and testing the coupled LIS-WRF system.

Also, CRREL is set to launch a new project in FY15 termed the Army Terrestrial-Environmental Modeling and Intelligence System (ARTEMIS). ARTEMIS is an effort to stand up a research, development, test, and evaluation platform composed of LIS and other modeling components. The goal of ARTEMIS is to establish a system that brings together capabilities of LIS with Army modeling systems and other software to establish an R&D prototype capable of delivering web-based Army content more directly suited for supporting mobility and maneuver support, military hydrology, scene and target simulation, sensor placement, and others. The ARTEMIS testbed would bring all NASA developed capabilities in the LIS infrastructure together with military applications to enable end-to-end systematic testing.

4.3.1.1 Snow science and product improvements

As the DoD leader in cold lands research and engineering, CRREL is on the leading edge of using remote sensing and model-based methods to characterize the snow pack and to link snow information with military utility. However, the ability to effectively characterize the snow pack hinges on new methods that link remote sensing with physical retrieval models through a data assimilation system, increasing the resolution and accuracy of current snow-cover and snow-depth products. Additionally, the snow products need to be tailored for support to military utilities that better support data to decision. In FY15, CRREL's Environmental Intelligence research and development work package will investigate improvements necessary to better characterize the snow pack using a data assimilation approach and will work toward better tailoring derivative products to bridge the data-to-decisions gap. The research team will work extensively to identify new post-processed snow analysis capabilities that they need to add for LIS to more directly support the broader DoD (including Army, Air Force, and Intelligence Communities) with focus on mobility, austere entry, targeting, and socio-cultural impacts.

4.3.2 NASA efforts

4.3.2.1 Vegetation health assimilation, including ETP

In the longer term, additional capabilities are needed to enable a full land surface assimilation and characterization capability in LIS. The ability to predict vegetation health using vegetation canopy physics—such as those being developed within the Noah-MP model—within the LIS is the next step in developing a full land surface characterization system. Vegetation has a significant impact on soil moisture and boundary layer energy, acting as the conduit to transfer moisture between the ground and the atmosphere through transpiration, and affecting overall atmospheric humidity (Wolf and Market 2007). Additionally, accounting for vegetation can be important for future support to scene simulation, target selection, and intelligence applications. An atmospheric and soil-water deficit affects vegetation also, degrading vegetation health in times of drought or extreme heat stress. The operational land surface models do not currently account for the influences of dynamic vegetation other than simple shading of the ground surface and bulk computations of evapotranspiration.

Current Noah LSM development has pushed for improved physical handling of vegetation effects. Several LSMs already include multi-layer canopy models (e.g., FASST, CLM). However, these models need to better account for carbon dioxide exchanges to more accurately simulate heat and vapor exchanges between the bulk plants and the atmosphere.

Physical model development and testing is important to enable the next phase—assimilating of vegetation properties from satellite sensors. There are current algorithms that attempt to diagnose a soil moisture profile through simple evapotranspiration; however, these remotely sensed methods rely on cloud free skies. Incorporating these capabilities as components of the vegetation algorithms in the LSMs or as capabilities within the LIS assimilation system would not only provide additional observations needed to properly diagnose soil moisture, but also would more explicitly identify and predict vegetation health. Improving measures of vegetation health and the influence that vegetation has on surface emissivity in both the IR and microwave frequencies is important for improving satellite radiance assimilation over land.

4.3.2.2 Satellite assimilation of cloud cleared radiances for skin temperature

NASA developed a capability to use the ensemble Kalman Filter in LIS to assimilate geostationary and polar orbiting satellite sensor IR frequency skin temperature data. This capability was never transitioned into AFWA, primarily because the capability was developed using the NASA Catchment land surface model instead of the Noah LSM because of physics limitations in the surface temperature computation in the Noah LSM at the time. The upgrades now available in the Noah-MP model should provide a method to assimilate surface temperature observations. Additionally, with the linking of LIS with the CRTM, pursuing the ability to assimilate cloud-cleared radiances for skin temperature should potentially provide a higher resolution option versus a gridded brightness temperature approach. NASA should test the skin temperature assimilation method with Noah-MP, given the relationship between LIS, Noah-MP, and WRF. The assimilation of skin temperatures will reduce LIS output skin temperature bias and improve the detection of clouds in CDFS-II.

4.3.3 AFWA in-house integration

During this period, AFWA should continue working with the Noah-MP physics in LIS and work toward implementing a Noah-MP option in the operational system. Additionally, continued integration and evaluation of the multi-parameterization options in LIS should continue with testing to support the PAIS.

4.3.3.1 Multi-model approach initial integration

One of the earliest LIS goals established under the previous LDP was to implement additional land surface models beyond the AFWA standard Noah LSM. The Community Noah LSM (Noah) is a well-established physics model with strong community support. It is co-managed by the National Centers for Environmental Prediction (NCEP) and NCAR, with input from AFWA; however, there are many additional LSM options in LIS that need to be evaluated for use in the ensemble modeling capacity. The

NCAR Community Land Model (CLM), NASA Catchment model, and Variable Infiltration Capacity (VIC) (Liang 1994) models are only a small sample of additional LSMs available in LIS; and all three have a team of community renowned scientists supporting continued development. Each of the models has additional product output options that could improve drought and hydrologic predictions. Also, there are more advanced physics options available in the other models that are not part of the Noah LSM. The ability to assimilate skin temperature products should be done with an LSM other than the heritage Noah LSM (e.g., NASA Catchment, Noah-MP), and the assimilation of GRACE satellite observations are only possible with land surface models that contain a groundwater component.

4.3.3.2 Begin testing drought prediction capability

Once a successful demonstration of an initial LIS-based drought-prediction capability has been accomplished, CRREL and AFWA should partner to transition the technology into an operational capability at AFWA, enabling AFWA to deliver both weather and climate products that support stability operations. The actual design of the capability will depend heavily on the results of the 2012–2013 NASA-CRREL research project; however, it will be important for this capability to have the ability for AFWA to run long term simulations with multiple land models, to assimilate new GRACE water storage and AMSR2 soil moisture observations, and to pull in NASA or NCEP produced seasonal predictions. This should not present scientific challenges for AFWA; rather, the challenges will be more infrastructural related (the ability to acquire new satellite data sources, to obtain seasonal prediction output, to access computing hardware to compute long term simulations, and to handle much heavier memory and storage demands than currently being used). AFWA will need to plan and coordinate these challenges with the NASA-CRREL team as they develop and design a drought prediction formula for DoD application.

4.4 FY16 development

4.4.1 CRREL efforts

4.4.1.1 Ensemble product development (mobility risk and hydrological risk)

In agreement with the general plan to move towards reducing the data-to-decision gap and increasing the utility of weather information available to support operations, a logical next step is migrating the current deterministic methods toward a risk-based approach and tailoring the products toward increased utility by mission operations groups, an implementation of ensemble-based capabilities. The methods for producing ensemble-based mobility products could range from a single mobility model using a range of weather information (perturbed soil moisture, precipitation, etc.) to one that includes variances within the mobility model. This preliminary development would initially focus on using the ensemble soil moisture analyses and predictions to initialize an array of mobility scenarios using a single deterministic mobility model (e.g., NRMM). The validation of this effort would focus on the systems' ability to generally describe real scenarios within an envelope of uncertainty. Refinement of the ensemble, to either reduce ensemble uncertainty or to better position the ensemble envelope around observations, would include improving and perturbing the mobility (hydrology, etc.) models. CRREL should consider multi-model options, and the research technical staff should conduct further studies to develop ensemble-weighting techniques.

4.4.1.2 Investigate the capability to predict reservoir storage levels (water security)

Expanding on stability operations support, developing new support options to predict water storage (reservoir height and lake levels) should be evaluated either using a LIS-only capability or a LIS-supported capability that feeds additional model, observation, and analysis systems. NASA and the US Department of Agriculture (USDA) currently monitor reservoir and lake levels using satellite altimetry data as the basis for water height measurements; however, there is no predictive component. Existing capabilities, including ERDC's streamflow and reservoir height prediction models (Downer et al. 2004a; Downer et al. 2004b; Downer et al. 2004c) and more recent CRREL and CHL collaboration on using LIS to initialize CHL watershed models (Eylander et al, 2012) highlight existing capabilities that exist to produce watershed predictive analyses; however, tying these capabilities to weather prediction models is the next step, for short term, long term, and seasonal forecasts. Predicting reservoir heights could be a component of the environmental intelligence system and supports international water treaty monitoring, stability operations, and other intelligence community operations.

4.4.2 NASA efforts

4.4.2.1 IMERG integration (assimilation-based precipitation analysis)

Precipitation is one of the most important input variables in an LSM. The previous LIS development plan focused heavily on improving precipitation forcing in LIS. This development plan will continue to focus on methods that will improve precipitation forcing; however, it should also evaluate additional methods for remotely diagnosing precipitation as additional options beyond use of surface observations or remotely sensed observations. In 2011, many of the global precipitation-measuring community members came together to collaborate on merging the best of several global precipitation analysis methods into a single precipitation analysis system. They intended the Integrated Multi-Satellite Retrievals for GPM (IMERG) to intercalibrate, merge, and interpolate all satellite microwave-based precipitation estimates together with IR-based estimates, gauge analyses, and any other precipitation analysis (Huffman et al. 2011). This NASA GPM mission-supported project is being designed to incorporate the latest advances in data blending, including using the Kalman filter techniques, to blend satellite data, to gauge observations, and to model estimates to design an advanced precipitation analysis engine. To continue a focus on providing the most accurate global precipitation analysis possible, evaluation and integration of advanced methods like those being developed in IMERG into LIS will be important. The IMERG algorithm could replace or update the CMORPH system, or the entire IMERG capability could be fully integrated into the LIS infrastructure.

4.4.2.2 Radiance-based assimilation (land surface temperature and soil moisture)

NASA should continue to push toward developing a radiance-based assimilation method for soil temperature and soil moisture. Previous fiscal year development of a skin temperature radiance-assimilation method will continue with additional focus put on passive microwave radiance assimilation for soil moisture. However, to develop a mature passive microwave radiance assimilation process, it is necessary to develop an improved microwave emissivity model. Ideally, NASA, NOAA, and DoD should push for the development of a microwave emission model and inclusion of necessary channels into the CRTM.

4.4.3 AFWA in-house integration

AFWA should consider integration of the ERDC-developed modeling capabilities, including maneuver support, hydrology, and dust prediction. AFWA's numerous database, computing, and software systems (e.g., LIS, WRF, terrain databases, etc) currently generate or already contain much of the data needed to drive mobility decisions. Development of a simple maneuver support system as a component of AFW-WEBS could be synergistic with higher fidelity capabilities housed within Army systems. Housing hydrology modeling could function in a similar fashion, with coarse resolution ensemble-based methods housed at AFWA for immediate decision-level products and higher fidelity products housed within Army programs of record where more deliberate decisions are needed.

4.5 FY17 development

4.5.1 CRREL efforts

During the FY17 period, CRREL will continue developing the Environmental Intelligence framework, building support for a variety of capabilities, including environmental support to stability operations, which includes support for food security, water security, and military operations. This will include an ensemble-based, risk prediction system used to support outlooks of groundwater availability, reservoir storage, domain-wide flooding risk, and other products all housed on a discoverable, open geospatial display system. The goal is to use the Environmental Intelligence system as a method of prototyping capabilities and to enable wide audience feedback prior to transitioning capability to an operational provider.

4.5.2 NASA efforts

This stage of LIS development will involve continuation of the integration of IMERG into LIS. This could be as a replacement for current CMORPH/GEOPRECIP/GFS precipitation processing components, which are then treated as "input data" in LIS, or as a completely integrated capability within the LIS infrastructure. Additionally, continued focus on satellite radiance assimilation for soil moisture and soil temperature should continue into this increment of LIS development.

Evaluation of vegetation product assimilation, with a goal on predicting vegetation health, should continue during this time. Several methods, including the SEBAL technique and others, use Infrared frequency satellite data to evaluate vegetation evapotranspiration (ET). Given the linkages between ET, weather, and soil moisture, linking ET measurements with the land surface model will increase opportunities to more accurately diagnose soil moisture and soil temperature from non-direct measurements and will also increase the options available for directly predicting vegetation health remotely.

4.5.3 AFWA in-house integration

Integration efforts will need to focus heavily on obtaining all the satellite data necessary to enable real-time assimilation of soil moisture, soil temperature, and vegetation properties. Incorporating, testing, and evaluating the radiance assimilation capabilities will also be important during this period.

A reevaluation, integration, and testing of the coupled LIS-WRF system should occur during this phase to enable AFWA to more directly support the many service options (products) being developed for LIS. This will include all the LIS post-processor flood, drought, and vegetation health components described in this paper that are not available in the WRF post-processor. Using output from the coupled LIS-WRF system, AFWA will need to test the support for maneuver modeling, austere entry, opportune landing, and other ground operations programs. Additionally, testing of a brown-out prediction capability using LIS-WRF will happen during this period.

5 Summary

This document describes a series of new development goals and provides a pathway to a more complete terrestrial characterization infrastructure capable of supporting a variety of DoD and Intelligence Community requirements. The focus on continuing to mature the infrastructure while also building new products will enable broader support for Army needs. Using LIS as the environmental source for application-layer support to maneuver operations, gap crossing, opportune landing, hydrology, scene simulation, target selection, and dismounted mobility will greatly increase the relevance and usefulness of LIS in the weather services infrastructure. Also important will be new opportunities to support human-environmental impact-based products that consider changing climate and seasonal weather shifts leading to drought and similar issues. Improving the linkages between weather, climate, and socio-cultural and socio-economic problems, topics described as Stability Operations, will become more important in the coming years. The resultant LIS infrastructure, if this plan is successful, will be capable of supplying the environmental data that supports a broad array of military operations and is relevant to large spectrum Army, Air Force, and IC users.

References

Downer, C. W., and F. L. Ogden. 2004a. Appropriate Vertical Discretization of Richard's Equation for Two-Dimensional Watershed-Scale Modelling. *Hydrological Processes* 18:1–22.

Downer, C. W., and F. L. Ogden. 2004b. GSSHA: A model for simulating diverse streamflow generating processes. *Journal of Hydrologic Engineering* 9(3):161–174.

Downer, C. W., and F. L. Ogden. 2004c. Prediction of runoff and soil moistures at the watershed scale: Effects of model complexity and parameter assignment. *Water Resources Research* 39(3). DOI:10.1029/2002WR001439.

Eylander, J., M. Follum, and J. D. Cetola. 2012. *Remotely Sensed Precipitation and Land Data Assimilation System supporting Hydrology and Hydraulics in Austere Environments*. AGU Chapman Conference on Remote Sensing of the Terrestrial Water Cycle, Kona, Hawaii, 19–22 February.

Foster, J. L., D. K. Hall, J. Eylander, G. Riggs, S. Nghiem, M. Tedesco, E. Kim, P. Montesano, R. Kelly, K. Casey, and B. Choudhury. 2011. A blended, global snow product using visible, microwave, and scatterometer satellite data. *International Journal of Remote Sensing* 32(5):1371–1395.

Frankenstein, S., and G. Koenig. 2004. *Fast All Season Soil STrength (FASST) Model*. ERDC/CRREL SR-04-1. Hanover, NH: US Army Engineer Research and Development Center. http://www.crrel.usace.army.mil/techpub/CRREL_Reports/reports/SR04-1.pdf.

Huffman, G. J., D. T. Bolvin, D. Braithwait, K. Hsu, R. Joyce, P. Xie, S. Yoo. 2011. *NASA Global Precipitation Measurement (GPM) Integrated Multi-satellitE Retrievals for GPM (IMERG): Algorithm Theoretical Basis Document (ATBD) Version 2.0*. Greenbelt, MD: Global Precipitation Measurement (GPM) mission, NASA Goddard Space Flight Center.

Liang, X. 1994. A Two-Layer Variable Infiltration Capacity Land Surface Representation for General Circulation Models. *Water Resources Series* TR140. Seattle, WA: University of Washington.

Kumar, S. V., C. D. Peters-Lidard, Y. Tian, R. H. Reichle, J. Geiger, C. Alonge, J. Eylander, and P. Houser. 2008. An integrated hydrologic modeling and data assimilation framework enabled by the Land Information System (LIS). *IEEE Computer* 41(12): 52–59. DOI:10.1109/MC.2008.475.

Kumar, S. V., R. H. Reichle, R. D. Koster, W. T. Crow, and C. D. Peters-Lidard. 2009. Role of subsurface physics in the assimilation of surface soil moisture observations. *Journal of Hydrometeorology* 10:1534–1547. DOI:10.1175/2009JHM1134.1.

Kumar, S. V., C. D. Peters-Lidard, J. Santanello, K. Harrison, Y. Liu, and M. Shaw. 2012. Land surface Verification Toolkit (LVT)—a generalized framework for land surface model evaluation. *Geoscientific Model Development* 5:869–886. DOI:10.5194/gmd-5-869-a.

Reichle, R. H., S. V. Kumar, S. P. P. Mahanama, R. D. Koster, and Q. Liu. 2010. Assimilation of satellite-derived skin temperature observations into land surface models. *Journal of Hydrometeorology* 11(5):1103–1122. DOI:10.1175/2010JHM1262.1.

Wolf, R. A., and P. S. Market. 2007. On the impact of corn and soybeans to the local moisture budget in Iowa. *National Weather Digest* 31:3–7. http://www.nwas.org/digest/papers/2007/Vol31-Issue1-Jul2007/Pg3-Wolf.pdf.

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14. ABSTRACT

In 2007, the Air Force Weather Agency (AFWA) approved a plan, collaborative with NASA Goddard Space Flight Center (GSFC), to partner on development of the Land Information System (LIS), an advanced software framework capable of supporting an operational and research-mode Land Data Assimilation System (LDAS) for weather and climate studies. The partnership led to the development of a structured 5-year plan to continue developing the LIS with newer science and software capabilities to improve the land surface characterization products at AFWA. The results were highly successful, leading LIS to be characterized as one of the most advanced LDAS systems available. This document builds on the successes of the initial 2007 LIS Development Plan (LDP07) and outlines incremental steps toward achieving a new set of goals not only to enable science and engineering achievements but also to deliver new capabilities of supporting soldiers and decision makers at all echelons of military support, from command level to small units. The new support opportunities include support for geospatial intelligence needs, including global drought (agricultural and hydrological) and hydrometeorology analysis and prediction, interfaces that enable LIS to support Army applications of maneuver support, additional work on the coupled LIS-WRF interfaces to improve support to dust lofting and brownout, as well as other infrastructure upgrades.

15. SUBJECT TERMS

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